Noise Reduction of Spiral Ducts

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The paper presents noise reduction (NR) of spiral ducts as a result of computational modeling of acoustic wave propagation. Three-dimensional models were created with the finite element method in COMSOL Multiphysics version 3.3. Nine models of spiral ducts with 1–9 spiral leads were considered. Time-harmonic analysis was used to predict NR, which was shown in spectral and interval frequency bands. Spiral duct performance can be seen as a comparison of NR before and after a change from a circular to a spiral duct.

spiral duct   noise reduction   sound propagation   computational modelling

1. INTRODUCTION

The Archimedean screw is a very popular solution in many industrial applications. This solution has been both useful and practical in many utilities and machines, e.g., in screw pumps, sewage treatment, augers in snow blowers and grain elevators, screw conveyors, etc. However, it has been impossible to find any information about the acoustic properties of a structural element which will be called a spiral duct in further considerations. That is why it is important to know the acoustic properties of screw leads inserted into the duct of a circular cross-section.

2. MODEL PARAMETERS

Nine models of spiral ducts with 1–9 spiral leads were considered. They were all solidly inserted into circular tubes 1 m in length and 125 mm in diameter (a typical length and diameter of pipes in ventilation systems). A 30 mm in diameter mandrel was placed in the axis of every spiral duct. The spiral profile was about 5-mm thick.

The elements thus constructed were called spiral ducts. Figure 1 shows three spiral ducts with 1–9 spiral leads.
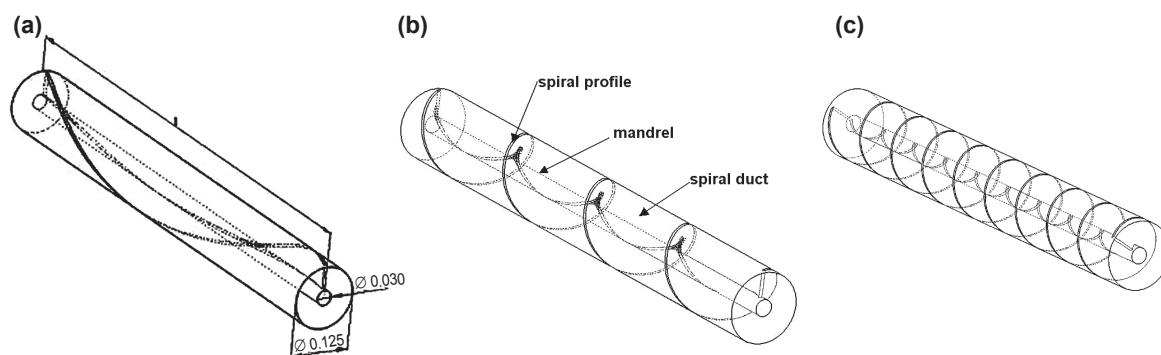

Figure 1. Sample spiral ducts inside a tube 1 m in length and 125 mm in diameter with a 30 mm in diameter mandrel in the axis. *Notes.* a—1 spiral lead, b—4 spiral leads, c—9 spiral leads.
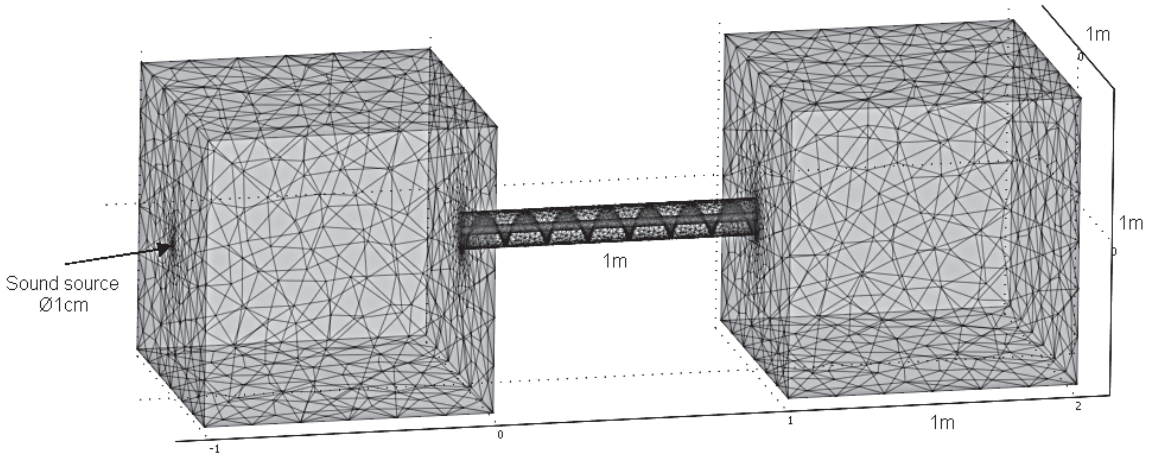
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Figure 2. A sample view of an acoustic system in COMSOL Multiphysics version 3.3 [1] with a generated finite element mesh.

3. PARAMETERS OF THE COMPUTATIONAL ENVIRONMENT

To simulate their acoustic properties, spiral ducts were designed as three-dimensional solid models. Solidworks version 2006 Education Edition, an engineering computer program, was used. Then they were imported into COMSOL Multiphysics version 3.3 [1]. This application uses the finite element method for computing sound wave propagation through ducts (Figure 2).

Figure 2 shows a computational system close to real conditions. It consisted of two air-filled 1-m^3 boxes, with characteristic impedance boundary conditions ($\rho_0 c$ = 1.25 [kg/m^3] • 343 [m/s]) [2]. Ducts were placed between them. A circular surface 1 cm in diameter was a harmonic sound source, which generated a plane wave of acoustic pressure of 1 Pa (94 dB). The source was located in the geometrical center of one of the walls of the box, opposite the duct inlet.

To solve this problem, a time-harmonic pressure acoustics application mode was used [1]. In Multiphysics the model equation is a slightly modified version of the Helmholtz equation [2, 3] for the acoustic pressure, *p*:

$$\nabla \bullet \left(-\frac{\nabla p}{\rho}\right) - \frac{\omega^2 p}{c_S^2 \rho} = 0, \qquad (1)$$

where *p*—acoustic pressure (Pa) depends on *x* (distance in meters) and frequency $\omega = 2\pi f$,

where *f*—frequency (Hz); ∇—gradient operator; ρ—air density (1.25 kg/m^3); c_S—sound speed in the air (343 m/s).

Equation 2 was used to determine sound attenuation [2, 3]:

$$NR = L_{in} - L_{out} \text{ (dB)}, \qquad (2)$$

i.e., *NR* is the difference between sound pressure levels (SPLs) L_{in} and L_{out} measured at 2 points in a silencer system located upstream (inlet) and downstream (outlet) of the silencer, respectively.

4. REAL DUCT VERSUS SIMULATION

To prove that virtual computing was very similar to reality, measurements in laboratory conditions [4] and the results computed in Multiphysics [1] were compared. Noise reduction (NR) in two circular tubes 1 m in length and 125 mm in diameter was examined. The results were almost identical (Figure 3). Thus, a real application of spiral ducts would probably produce almost the same results as those numerically computed.
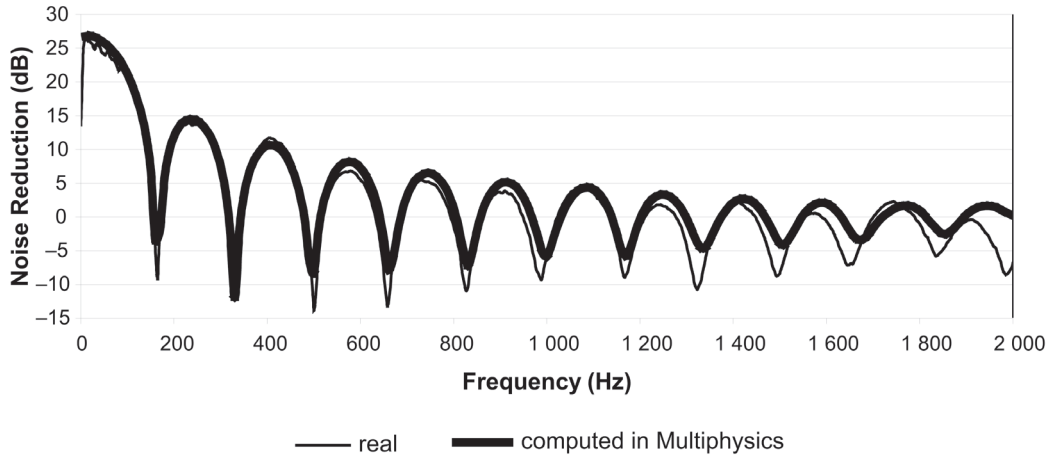
Figure 3. Comparison of noise reduction for a tube 1 m in length and 125 mm in diameter computed in COMSOL Multiphysics version 3.3 [1] and that measured in laboratory conditions.

5. CALCULATION OF NR OF SPIRAL DUCTS

As in practice an engineer needs concrete directions and parameters of a technical object, NR was used as a practical determinant of sound attenuation. To improve the usefulness of the technical solution, detailed parameters were required. Therefore, every duct was analyzed in frequency-dependent parametric attenuation, and averaged over some frequency bands. Equation 3 defines band NR from a lower frequency limit f_{low} to a higher frequency limit f_{high} (Hz), which is designated as $NR_{(f_{low} - f_{high})}$:

$$NR_{(f_{low} - f_{high})} = L_{in(f_{low} - f_{high})} - L_{out(f_{low} - f_{high})} (dB),$$

(3)

where L_{in}—SPL equivalent at the inlet of the duct (dB), L_{out}—SPL equivalent at the outlet of the duct (dB), $f_{low} - f_{high}$—frequency band (Hz).

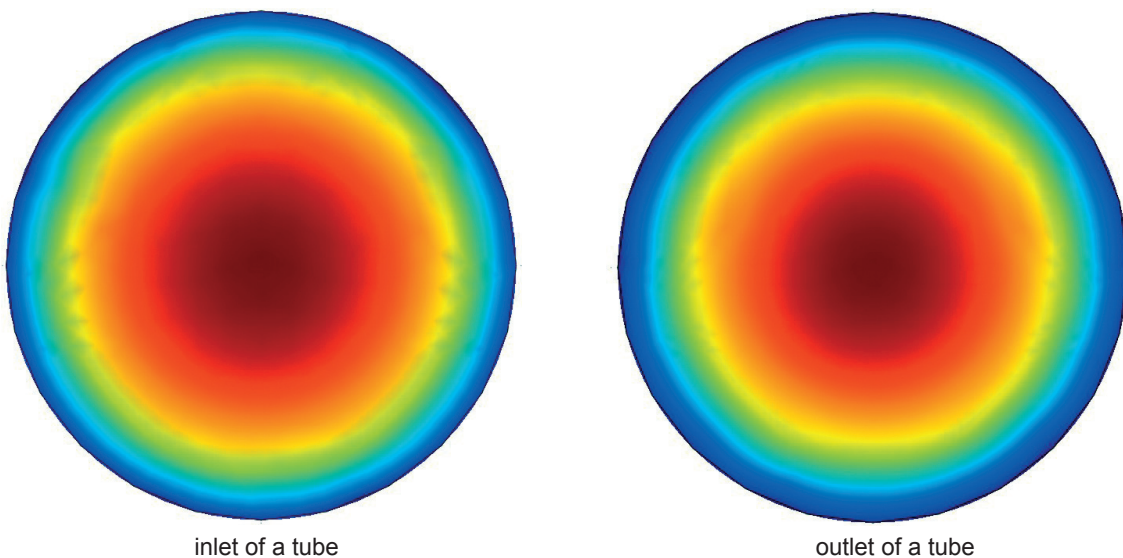inlet of a tube   outlet of a tube

Figure 4. An example of sound pressure level distribution at the inlet and outlet surfaces of a circular tube 1 m in length and 125 mm in diameter, at 320 Hz.
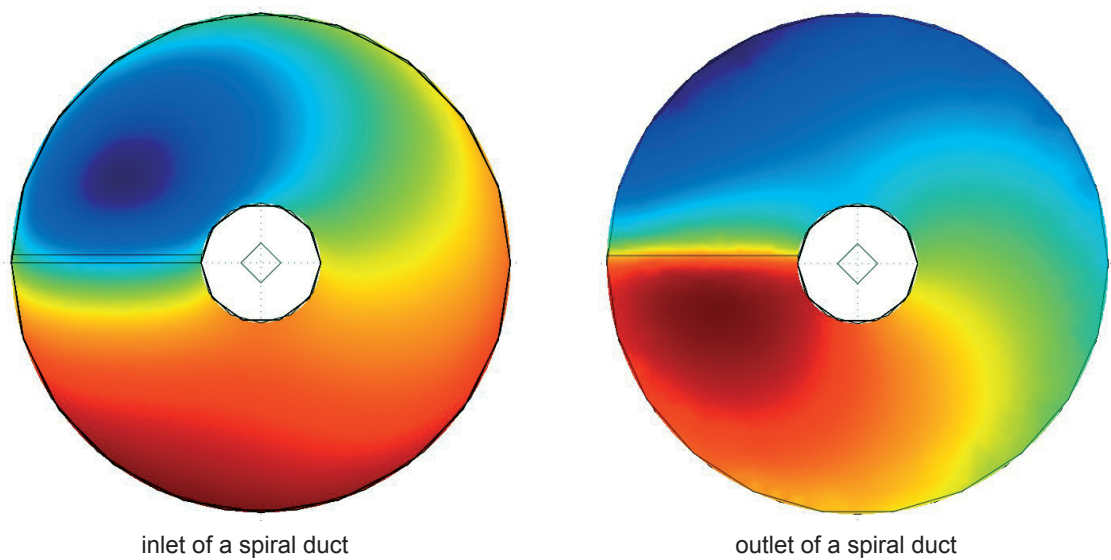
inlet of a spiral duct   outlet of a spiral duct

Figure 5. An example of sound pressure level distribution at the inlet and outlet surfaces of a spiral duct with 6 spiral leads, at 320 Hz.
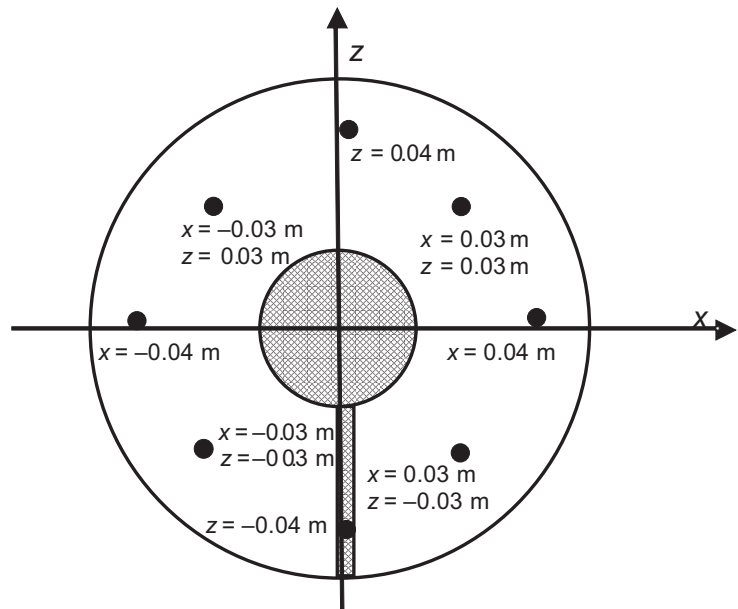

Figure 6. Location of 8 points on measured surfaces at the inlet and outlet of spiral ducts in COMSOL Multiphysics version 3.3 [1] for averaging sound pressure levels.

A numerical calculation of the averaged band $NR_{(f_{low}-f_{high})}$ (Equation 3) is expressed as

$$NR_{(f_{low}-f_{high})} = 10\log\left(\frac{\sum_{i=1}^{n}10^{0.1\cdot L_{in,i}}}{\sum_{i=1}^{n}10^{0.1\cdot L_{out,i}}}\right) \quad (dB), \quad (4)$$

where *n*—number of calculation intervals (calculation steps), $n = (f_{low} - f_{high})/\Delta f$, Δf—frequency interval (Hz), a step in numerical calculations (here $\Delta f = 10$ Hz).

SPL distribution at the inlet and outlet surfaces of the circular tube made it possible to make measurements directly in one point in the central axis (Figure 4). In contrast, SPL distribution at the inlet and outlet surfaces of spiral ducts was
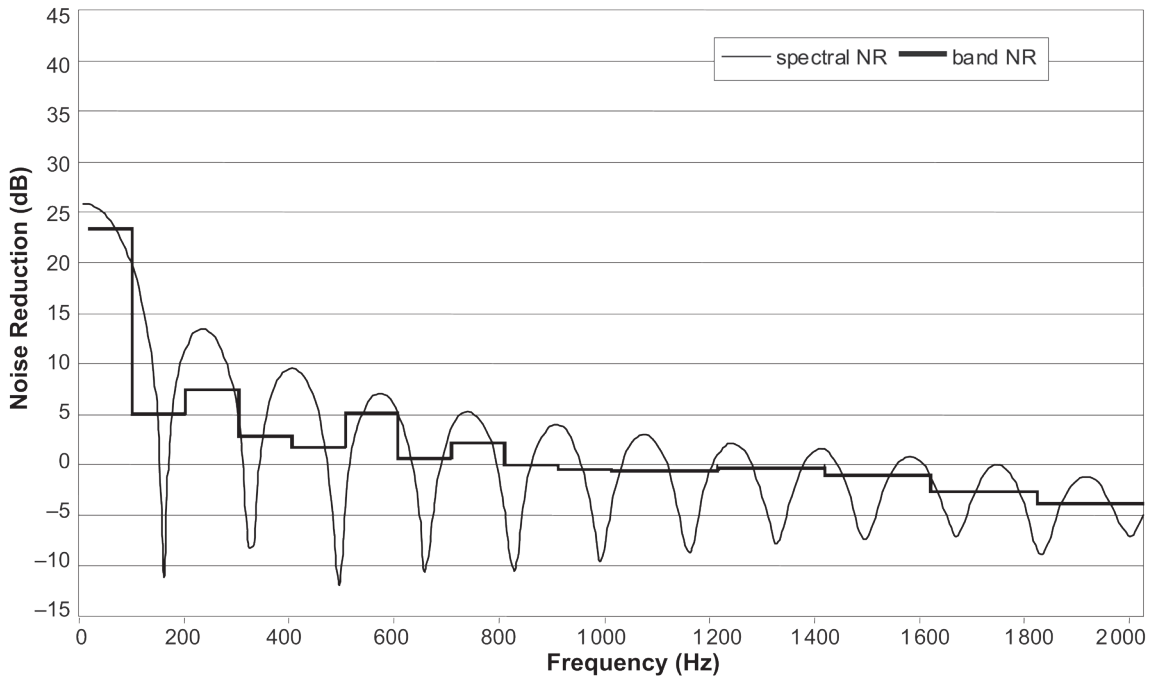
Figure 7. Spectral and band noise reduction (NR) for a tube 1 m in length and 125 mm in diameter.
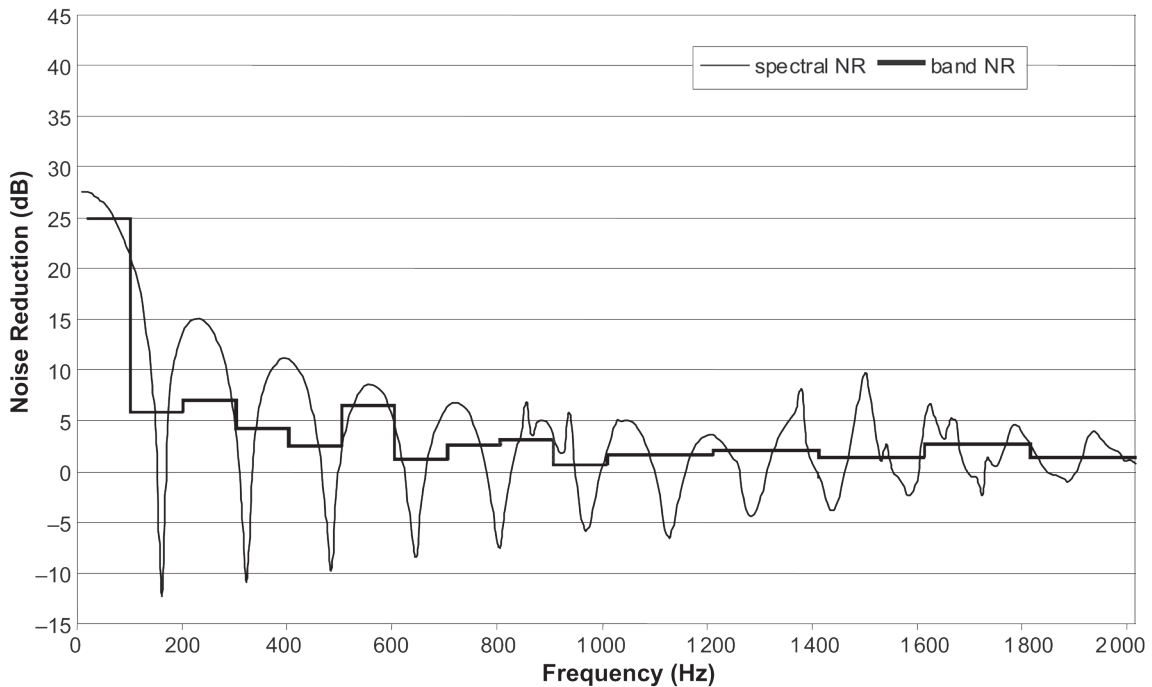

Figure 8. Spectral and band noise reduction (NR) for 1 spiral lead in tube a 1 m in length.

different (Figure 5). Therefore, band $NR_{(f_{low}-f_{high})}$ was calculated on the basis of average SPL in 8 points on the inlet and outlet surfaces (Figure 6).

Figure 7 presents spectral and band $NR_{(f_{low}-f_{high})}$ for a circular empty tube 1 m in length and 125 mm in diameter. Figures 8, 9 and 10 show spectral and band NR for a few types of spiral ducts. The frequency band for band NR was divided into sections 20–1000 Hz, with 100-Hz intervals, and 1000–2000 Hz, with 200-Hz intervals. These untypical acoustic frequency ranges were used to show the NR differences between the investigated spiral ducts calculated with a 10-Hz step.
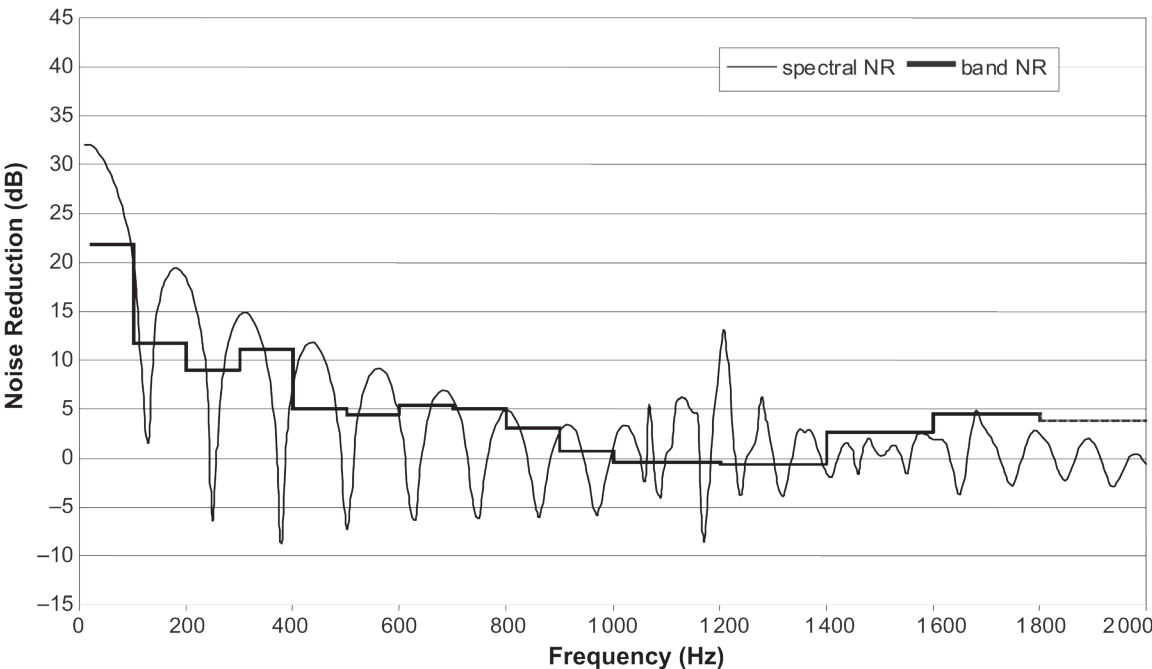
Figure 9. Spectral and band noise reduction (NR) for 4 spiral leads in a tube 1 m in length.
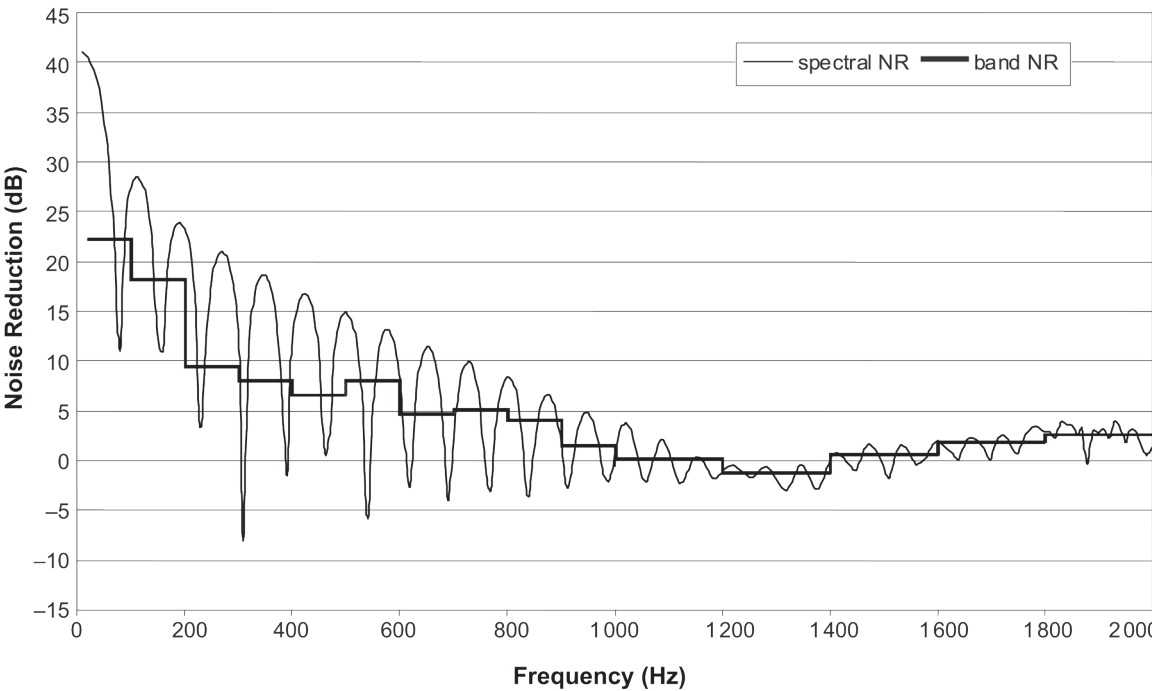

Figure 10. Spectral and band noise reduction (NR) for 9 spiral leads in a tube 1 m in length.

Table 1 shows accurate values of band NR, in particular frequency bands for all modeled spiral ducts. Two additional frequency bands are included: 20–2000 Hz, which provides global information about sound NR, and 20–800 Hz, which provides information about sound NR in the low- and mid-frequencies.

Table 1 shows that the addition of a spiral lead to an empty tube results in additional noise reduction. More importantly, this property is almost linear (see the envelope in Figure 11), i.e., the more leads, the more noise reduction.
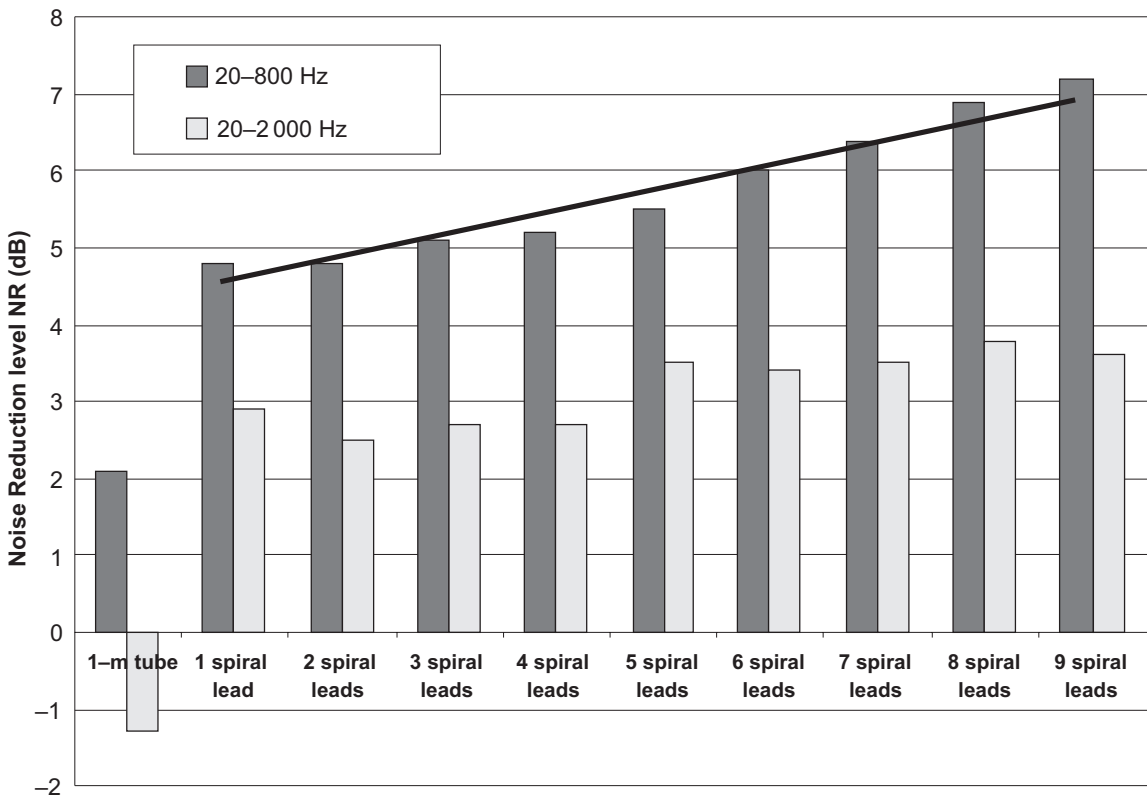
Figure 11. Noise reduction for 9 spiral ducts and a tube 1 m in length and 125 mm in diameter, in the 20–800 Hz frequency band.

TABLE 1. Band Noise Reduction for Spiral Ducts and an Empty Tube 1 m in Length and 125 mm in Diameter

| Frequency (Hz) | Tube | Noise Reduction (dB) | | | | | | | | |
| | | Number of Spiral Leads | | | | | | | | |
		1	2	3	4	5	6	7	8	9
20–100	23.4	26.7	27.3	27.8	27.8	26.1	12.9	17.3	23.0	23.2
100–200	5.0	7.6	9.1	11.4	13.4	13.2	10.1	13.6	12.9	19.2
200–300	7.5	8.9	5.0	4.9	7.4	12.0	9.7	9.6	10.2	10.6
300–400	2.8	6.0	9.9	8.5	5.3	8.2	8.9	7.3	12.2	9.1
400–500	1.8	4.3	4.5	5.9	5.9	6.4	7.4	7.1	6.4	7.8
500–600	5.1	8.3	5.2	4.5	6.6	5.7	6.1	7.1	5.8	9.2
600–700	0.6	3.0	5.3	4.8	4.2	5.3	4.8	6.6	6.9	6.1
700–800	2.2	4.4	3.2	4.7	3.8	4.4	3.6	5.6	6.6	6.6
800–900	−0.1	4.9	3.0	3.0	2.9	2.8	2.7	3.7	4.7	5.6
900–1000	−0.5	2.1	3.7	2.8	2.0	1.8	1.7	2.0	2.5	3.2
1000–1200	−0.5	3.4	3.0	3.7	3.8	1.4	1.1	1.2	1.5	2.0
1200–1400	−0.3	3.3	2.4	5.4	3.3	3.5	2.7	0.9	0.7	0.8
1400–1600	−1.0	2.1	2.9	3.0	2.3	3.8	3.9	4.2	3.1	1.9
1600–1800	−2.6	3.3	2.1	2.1	2.3	4.3	4.7	4.8	5.8	4.2
1800–2000	−3.8	2.7	2.3	1.4	1.5	2.6	2.8	4.5	5.8	4.9
20–800	2.1	4.8	4.8	5.1	5.2	5.5	6.0	6.4	6.9	7.2
10–2000	−1.3	2.9	2.5	2.7	2.7	3.5	3.4	3.5	3.8	3.6

6. CONCLUSIONS

- NR in spiral ducts is better than in circular ducts in the examined frequency range of 20–2 000 Hz;
- increasing the number of spiral leads results in bigger NR in the low- and mid-frequencies of 20–800 Hz; and
- the newly defined band noise ratio is a good measure of averaged acoustic properties.

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